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KNOWLEDGE-AIDED SENSOR SIGNAL PROCESSING & EXPERT REASONING
Workshop—02 • Washington, DC

Radar Phenomenology Modeling and High-Fidelity Data Generation*

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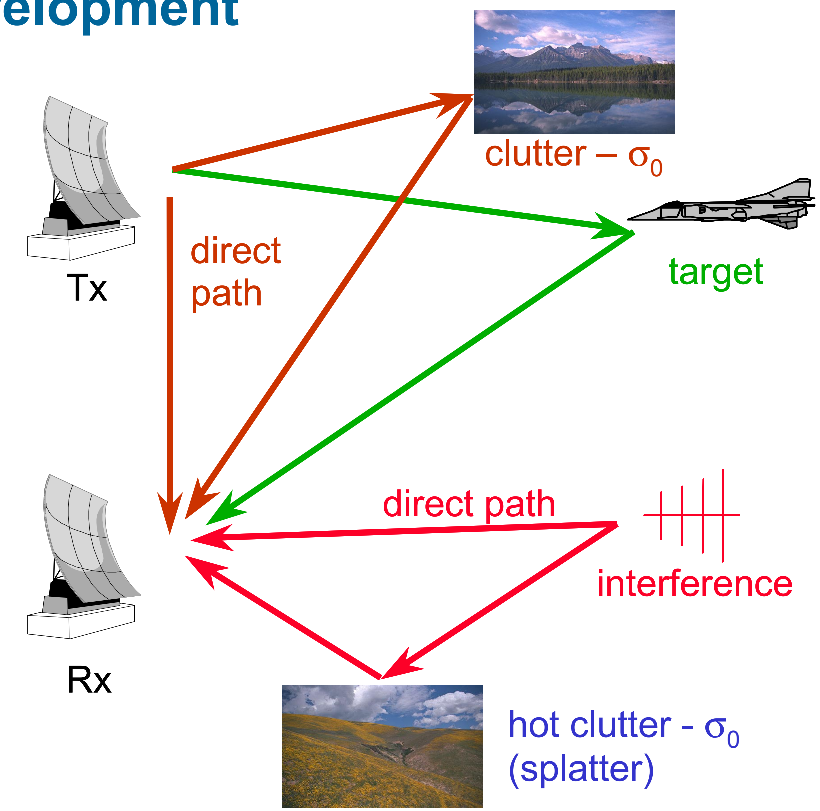
Outline

- **RF phenomenology modeling**
  - overview of the Splatter, Clutter, and Target Signal (SCATS) model
  - ground scatter modeling
  - comparison to experimental data
- **Other effects**
  - internal clutter motion (ICM)
  - ground traffic
  - discrete scatterers
  - array calibration
- **Heterogeneous clutter example**
  - effects of heterogeneous terrain
  - effects of ICM
  - effects of ground traffic
- **Overview of KASSPER-02 Workshop data set**
- **Summary**

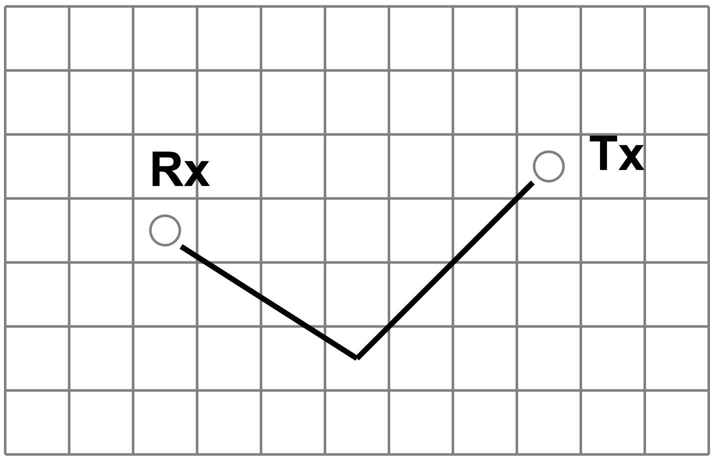
Splatter, Clutter, and Target Signal Model

- **Developed under a number of DARPA, Army, Navy, and Air force programs since 1989**
- **Provides characterization of complex RF environments**
- **Uses include system analysis, test planning, signal processing algorithm development**
- **The model provides characterization of:**
  - target return
  - direct path signal
  - ground scattered signal (clutter for radar)
  - direct path signal from interferer
  - ground scattered interference signal (hot clutter, splatter, or terrain-scattered interference)



Ground Scatter Modeling

- Transmit and receive locations defined, along with an area of calculation
- Area of calculation is divided into a grid of user defined cell sizes
- Propagation to each cell is calculated used DTED-based terrain profiles and SEKE
- Power received per unit area from each cell calculated by using radar equation
- Provides signal strength, path range, path Doppler, and AoA for each scattering patch
- Other effects (e.g. ICM, discretes, ground traffic) may be added



$$P_{r_k} = \frac{P_t G_{t_k} F_{t_k}^2}{4\pi R_{t_k}^2} \frac{\sigma_0 F_{r_k}^2}{4\pi R_{r_k}^2} \frac{G_{r_k} \lambda^2}{4\pi}$$

Scattering Coefficient

Constant scattering coefficient

"Monostatic equivalent" model

- use measured monostatic data from *Radar Cross Section Handbook*
- apply bistatic equivalence theorem by choosing scattering coefficient as a function of the angle between terrain local normal and the bistatic bisector of the incident and scattered rays

Two-scale composite models

- two scale of roughness model
- polarization dependent
- based on surface roughness parameters
- modified version from *RCS Handbook* using Phillips height spectrum rather than Gaussian

Polarimetric (Composite) Models

- **Polarized fields from a (tilted) dipole**
  - find polarization vector
  - resolve into horizontal (TE) and vertical (TM) components
  - calculate gain for each component
- **Convert to coordinates of plane tangent to the local terrain**
- **Calculate scattering coefficient σ_0 for each component (HH, HV, VH, VV)**
- **Calculate received power for each component**
- **Combine components incoherently**

$$P_R = \frac{P_T}{(4\pi r_1^2)(4\pi r_2^2)} \frac{\lambda^2}{4\pi} \left[\begin{array}{c} G_T^H F_T^H \sigma_0^{HH} F_R^H G_R^H + G_T^H F_T^H \sigma_0^{HV} F_R^V G_R^V + \\ G_T^V F_T^V \sigma_0^{VH} F_R^H G_R^H + G_T^V F_T^V \sigma_0^{VV} F_R^V G_R^V \end{array} \right]$$

Two Scale Composite Models

Two scales of roughness model

- large scale, physical optics ('quasi-specular') contribution
- small scale, perturbation ('Bragg-scatter') contribution

Polarization dependent

- function of incident and scattered polarization (HH,HV,VH,VV)
- rough surface scattering has strong polarization dependence

Based on surface roughness parameters

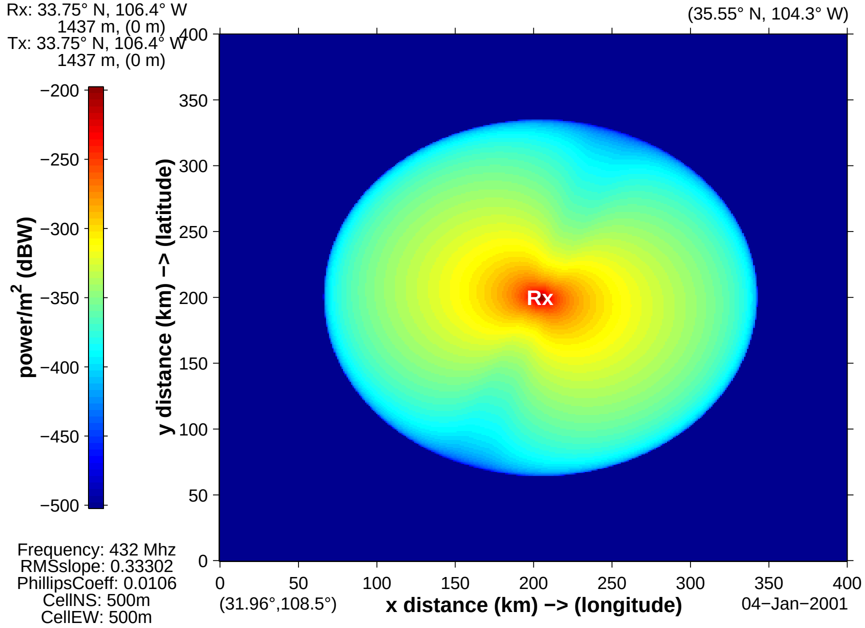
- large scale heights, correlation lengths and/or slopes
- small scale heights, correlation lengths and/or slopes

Height spectrum - Gaussian (*RCS HB*) vs. Phillips

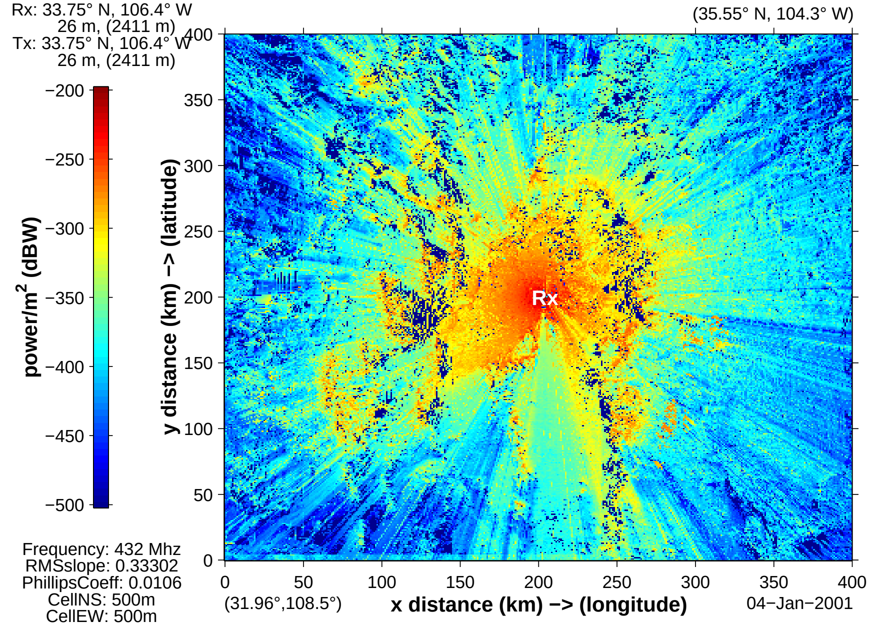
- statistical representation of surface roughness
- impacts parameter selection
- Phillips height spectrum primarily used in SCATS

Mountain Top Monostatic Clutter

bald earth

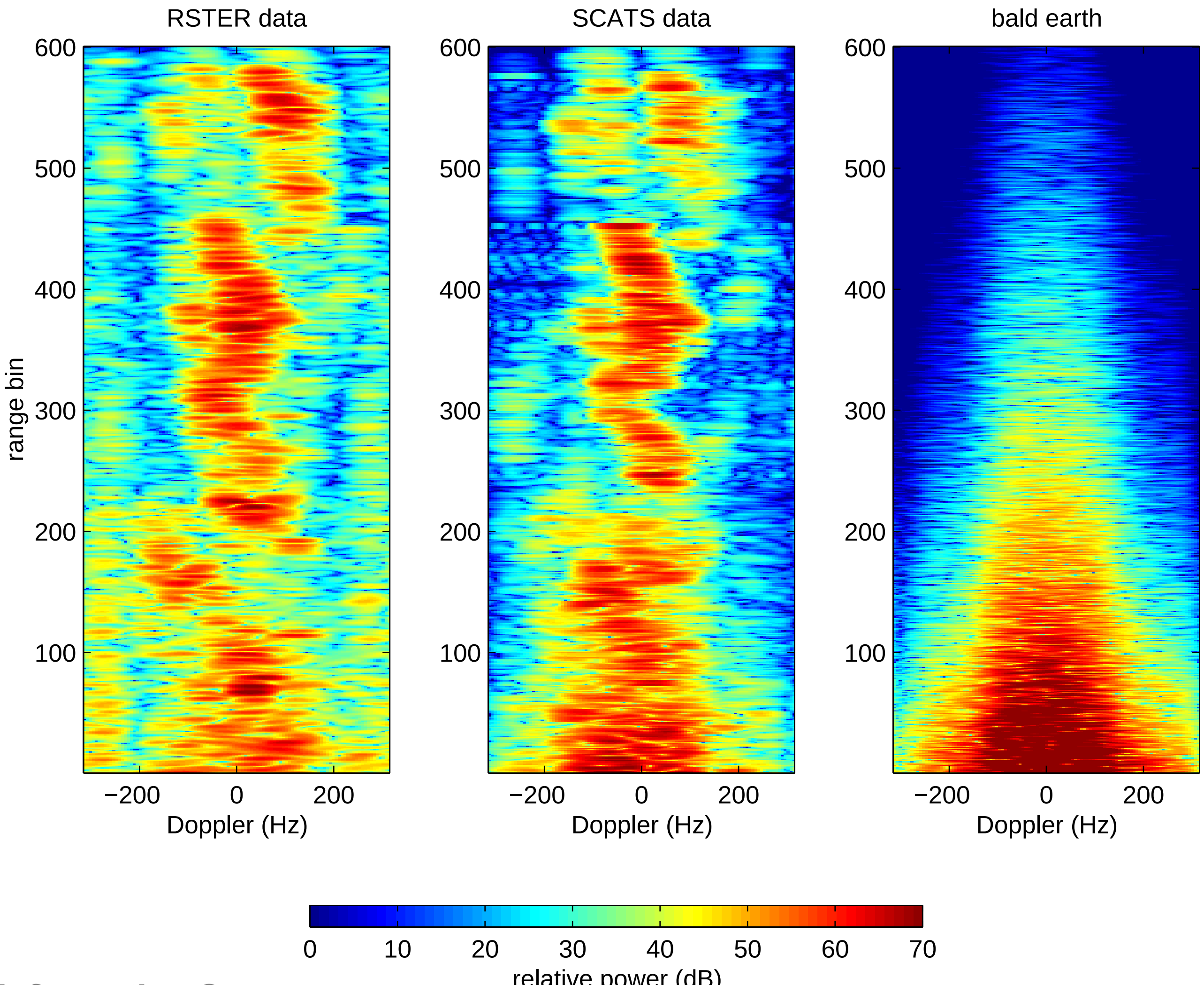


DTED



- Simulated clutter maps using ‘bald earth’ and DTED shown
- Radar parameters match Mountaintop IDPCA65v1 data
- Significant differences observed between bald earth and DTED simulations

Mountain Top Monostatic Clutter (cont.)



- Range-Doppler clutter maps shown for RSTER and SCATS simulations
- SCATS results shown both with and without DTED
- SCATS w/ DTED results in a significantly better match to the experimental data
- SCATS captures a majority of the clutter features

Mountain Top Bistatic Scatter

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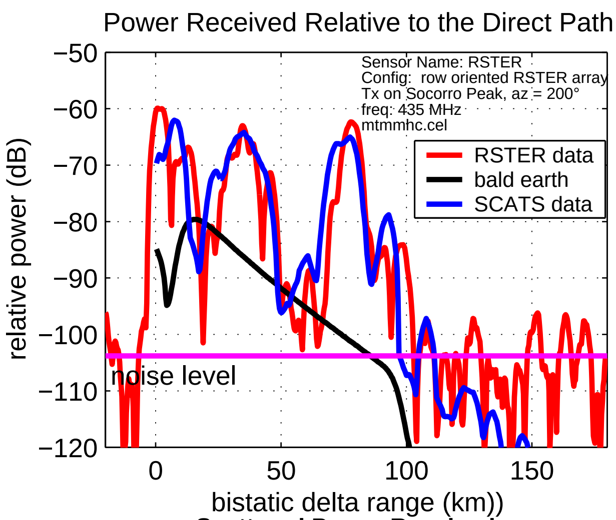
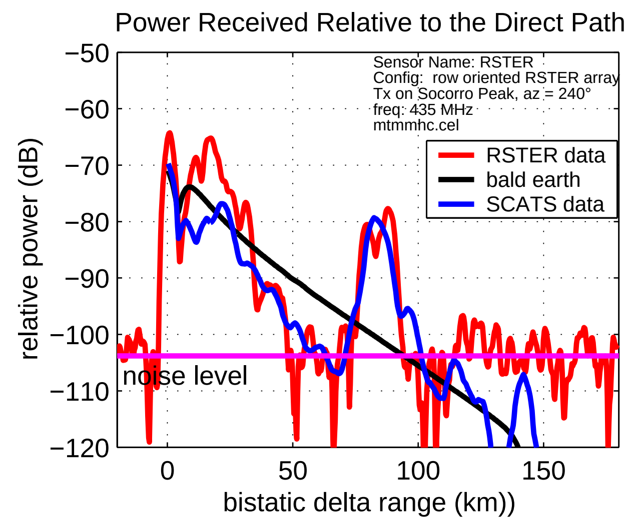
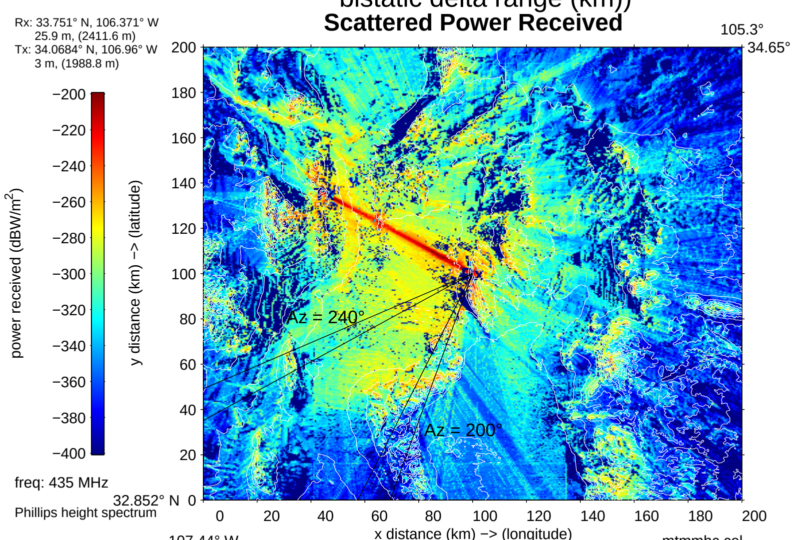
Az = 200°





Az = 240°



- **Comparison of delay spread for RSTER (Mountain Top) data and SCATS**
- **Power relative to direct path power plotted**

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Internal Clutter Motion Model

- **Billingsley empirical model has DC term plus an AC (noise) component:**

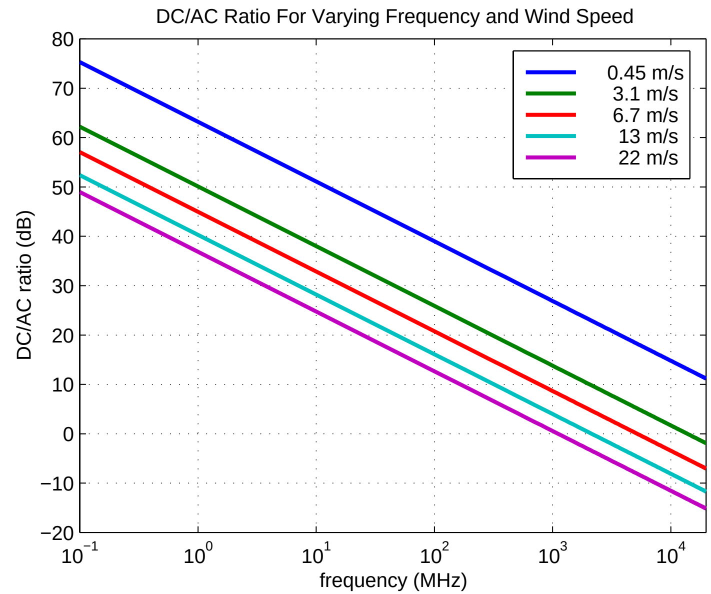
$$P(v) = \frac{r}{r+1}\delta(f) + \frac{1}{r+1}\frac{\beta\lambda}{4}e^{-\frac{\beta\lambda}{2}|f|}$$

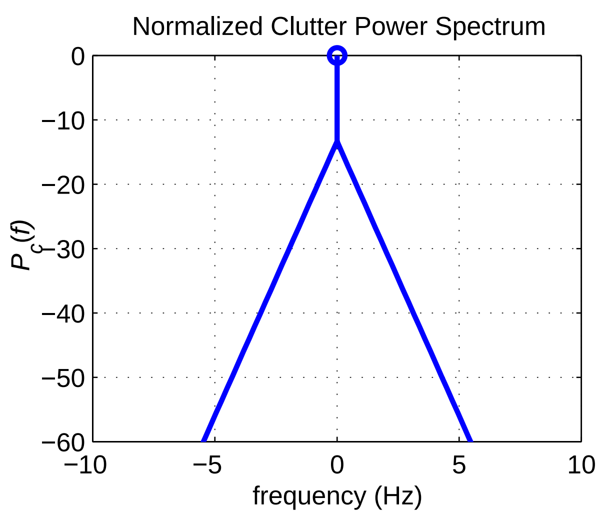
- **DC/AC ratio r is found from:**

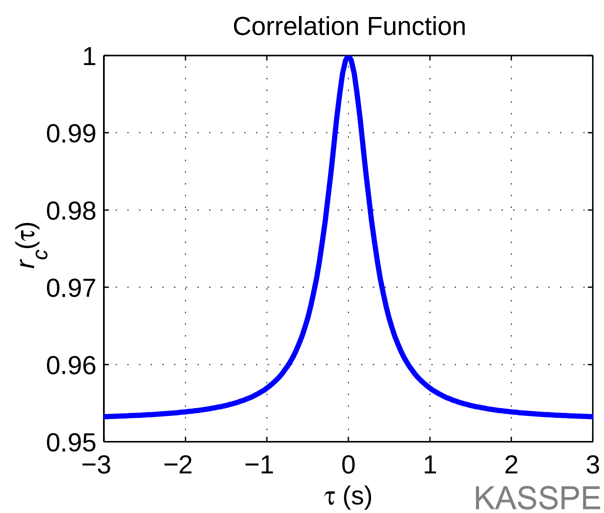
$$10\log r = -15.5\log w - 12.1\log f_c + 63.2$$

- **Correlation (covariance matrix taper or CMT) function becomes:**

$$r_c(\tau) = \frac{r}{r+1} + \frac{1}{r+1}\frac{(\beta\lambda)^2}{(\beta\lambda)^2 + (4\pi\tau)^2}$$







Clutter Discretes

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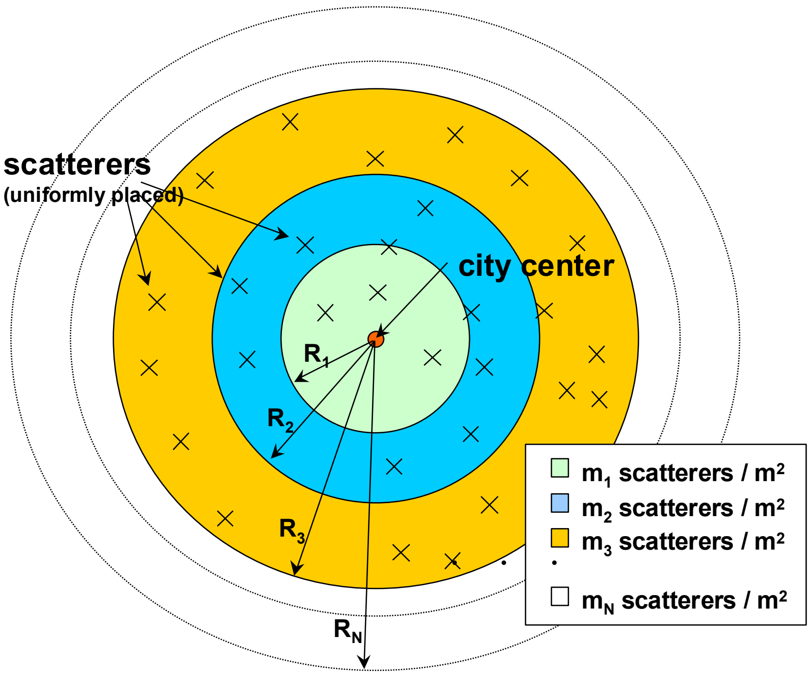

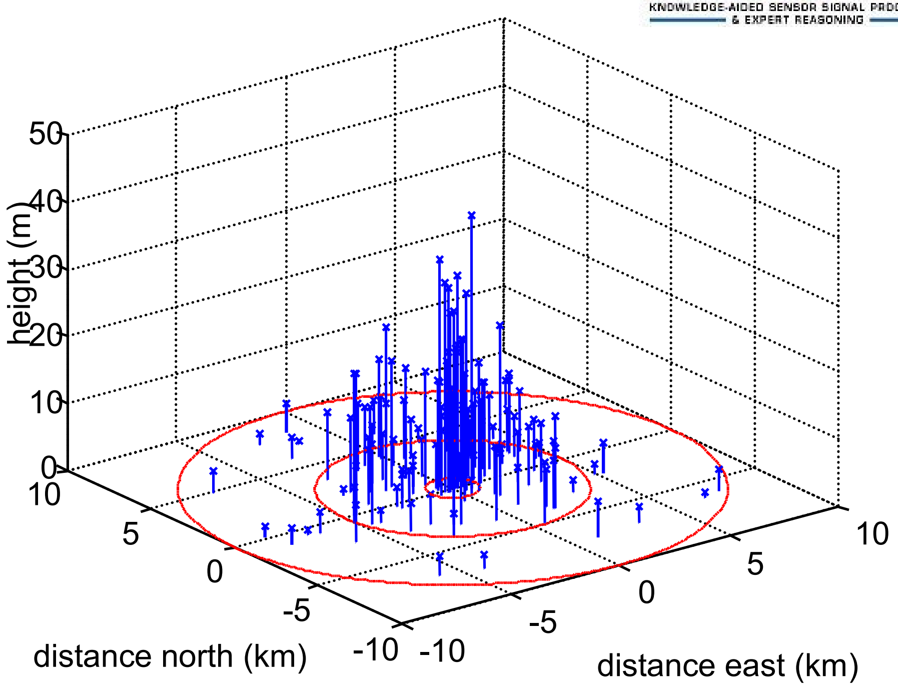

- Can produce under-nulled clutter due to training methods
- Discrete density is a function of population centers
- Closer to population centers => greater probability of a discrete
- Larger RCS discretes closer to population centers

Ground Traffic Model

- Road data extracted from Census Bureau TIGER/Line database
- Ground traffic placed along the road segments using an exponential distribution to achieve a Poisson traffic arrival distribution
- Latitude and longitude calculated for each vehicle - two sets of vehicle positions per segment (opposing lane assumed)
- Traffic clutters can be placed as desired
- Representative example distribution of ground traffic:

	Cars	Trucks
% of total traffic	80 %	20 %
Avg spacing	50 m	50 m
Speed on Interstate	60 mph	60 mph
Speed on US Hwy	50 mph	50 mph
Avg RCS	5 dBsm	15 dBsm
RCS fading model	Rayleigh	Rayleigh

Array Calibration Errors/Channel Mismatch

Angle-independent channel complex gain errors

- gain and phase errors on each channel due to errors in line lengths, receiver gain, etc.
- manifests as rank-one CMT on (total) signal covariance
- alternately may view as full rank (orthonormal if phase only) transformation of the array data

Angle-dependent array manifold errors

- results from
  - element position errors
  - mutual coupling
  - element/super element pattern errors
- manifests as separate, angle-dependent rank-one CMT on each signal incident on the array

Channel mismatch

- channel mismatch across the element/receiver band reduces ability to cancel clutter (i.e., varying channel transfer functions)
- rank of CMT on total signal covariance > 1

Simulation of Calibration Errors/Channel Mismatch

Angle-independent calibration errors

- complex gain errors (i.e., amplitude and phase)
- results from line length variations, receiver characteristic variations, etc.

Angle-dependent calibration errors

- modeled by element position errors on each subarray
- element position errors consistent with ~35 dB achievable sidelobes (Taylor weighting)
- element position errors independent from subarray to subarray (each subarray has a different gain pattern)

Channel mismatch

- transfer function mismatch channel to channel
- implementation more complex – to be included in later data sets

Future Simulation Features

- More extensive use of land use and land cover data (LULC)
- Improved propagation models for SBR
- Bandwidth effects – decorrelation across array face
- Realistic target and ground traffic RCS (probability distribution) based on models or measurements
- EM model-based subarray and channel calibration errors
- Channel transfer function mismatch

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Heterogeneous Clutter Example

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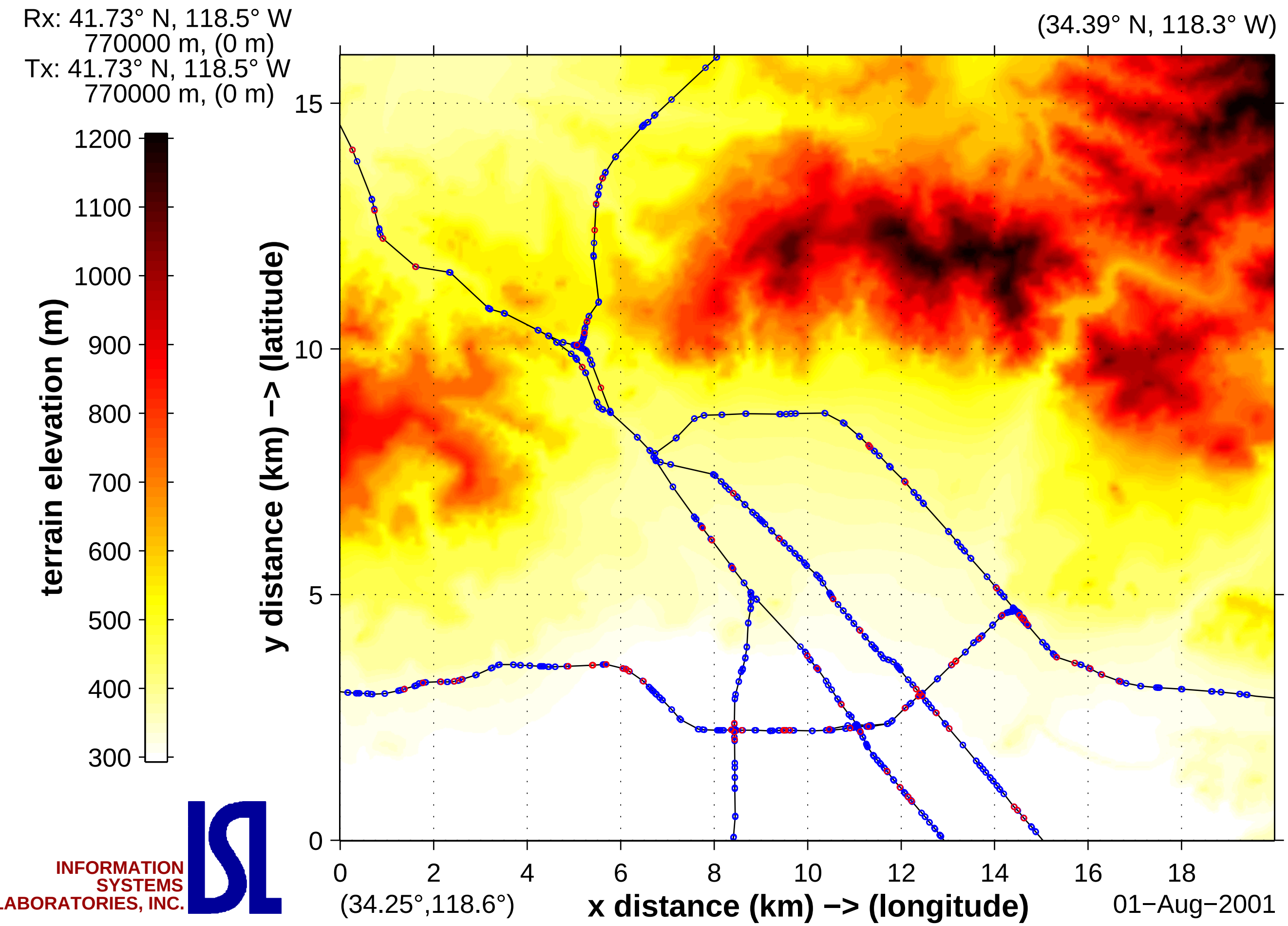

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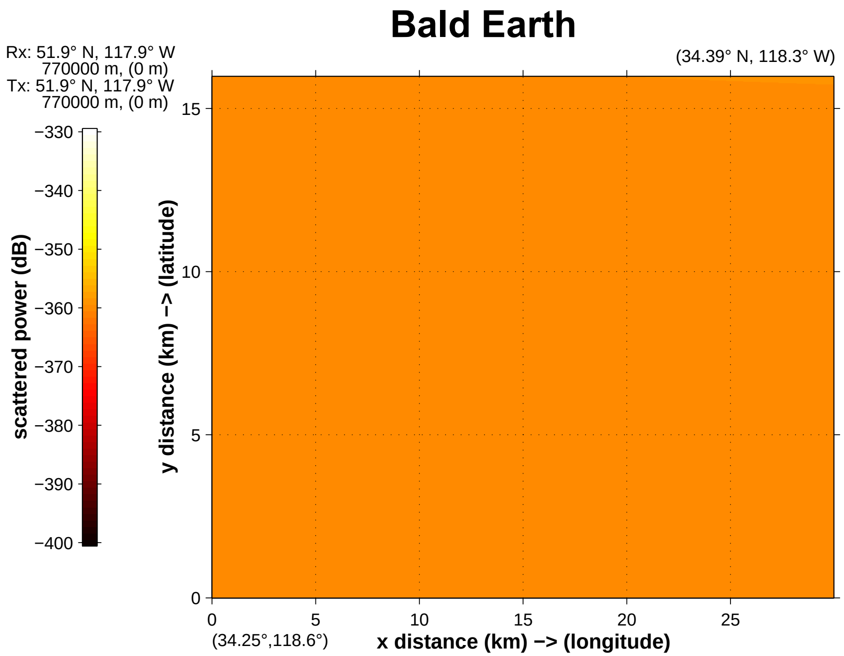
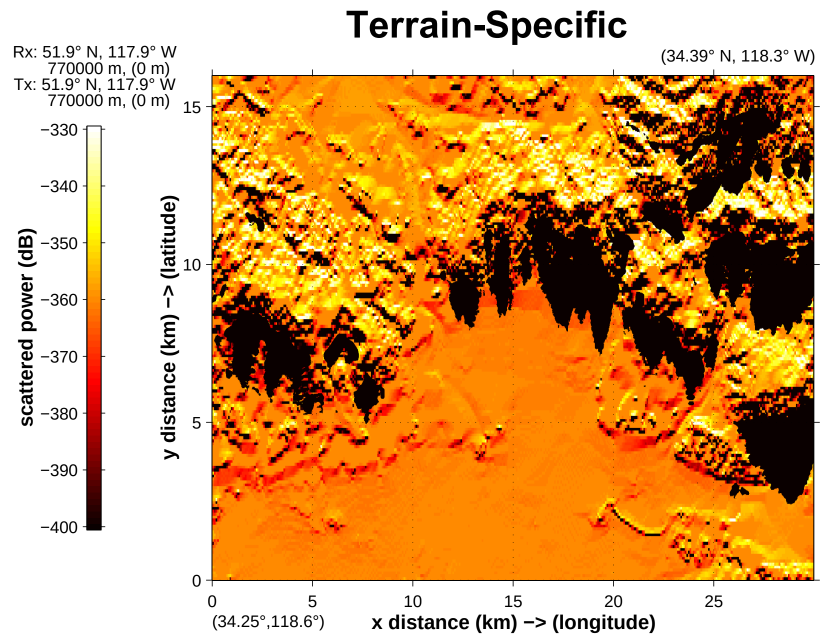
Site-Specific Terrain Effects





- **X-band LEO space-based radar example**
  - 770 km altitude
  - speed of 7 km/s
- **Comparison of bald earth and terrain-specific clutter**
- **Grazing angle of ~15°**

Site-Specific Terrain Effects (cont.)

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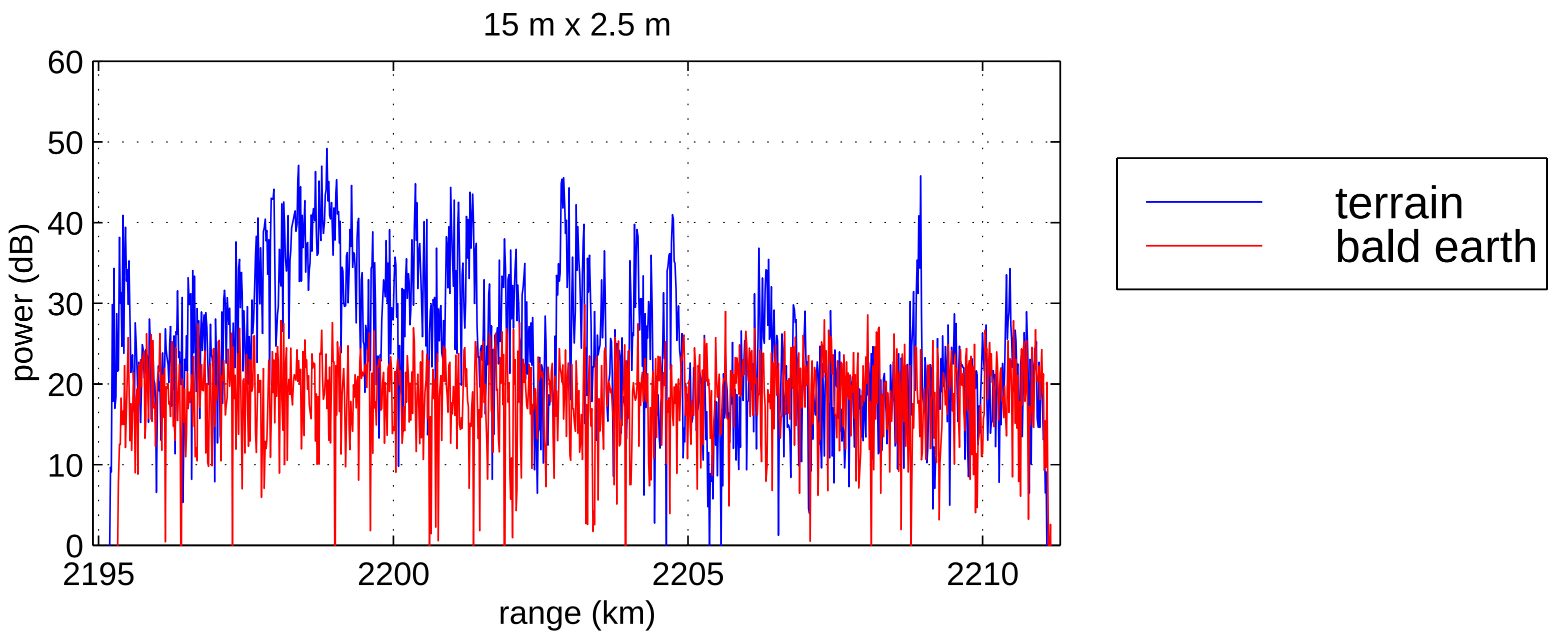
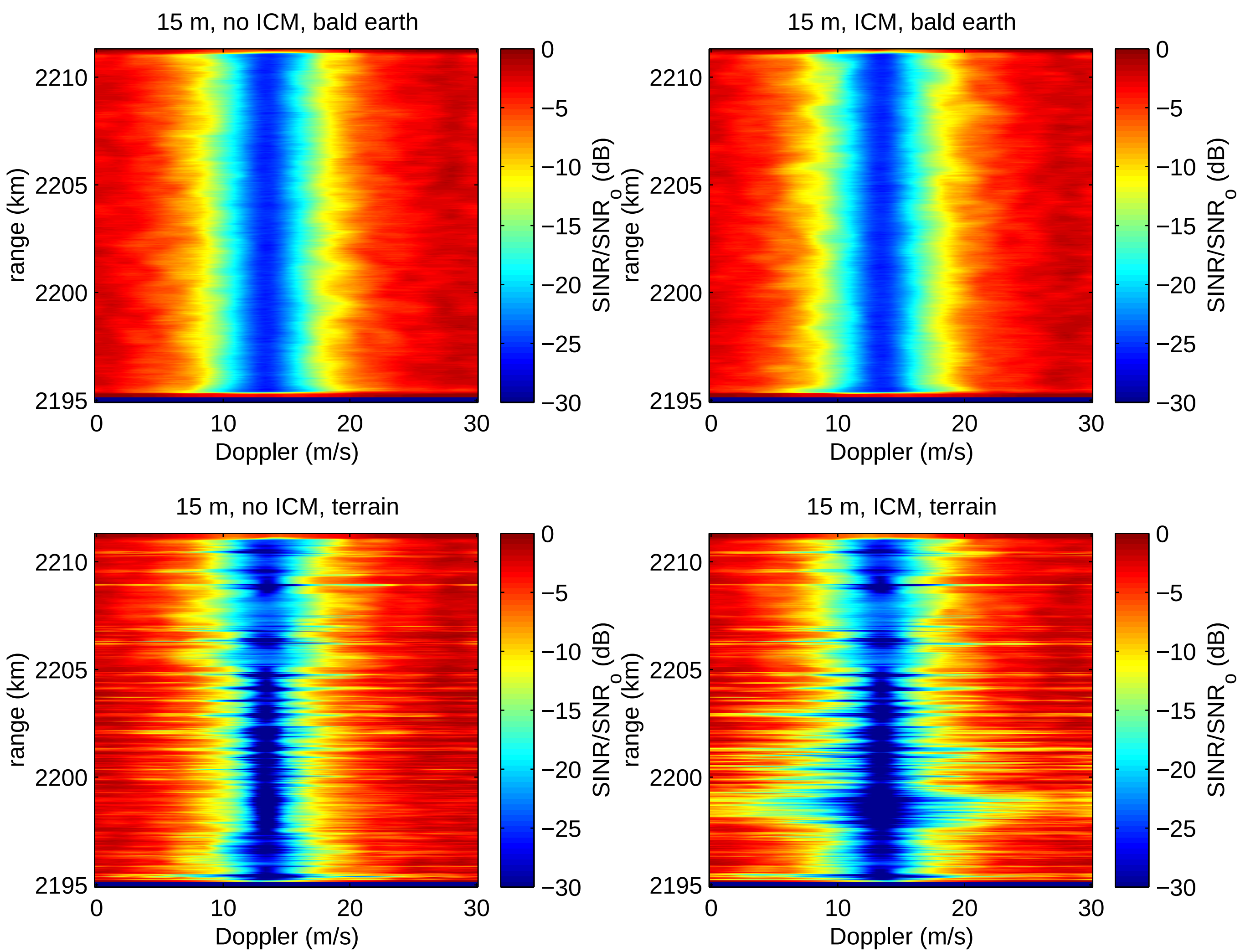


- **Power versus range shown for a full aperture beam**
- **Hamming pattern**
- **Significant Clutter amplitude variations**
- **Grazing angle ~15°**

Heterogeneous Terrain Impact on SINR



- **DoFs: 10 pulses, 5 beams**
- **100 training bins**
- **10 dB diagonal loading**
- **15 m x 2.5 m aperture**
- **Grazing angle ~15°**
- **Terrain effects result in under-nulled clutter**

Ground Traffic Effects Example

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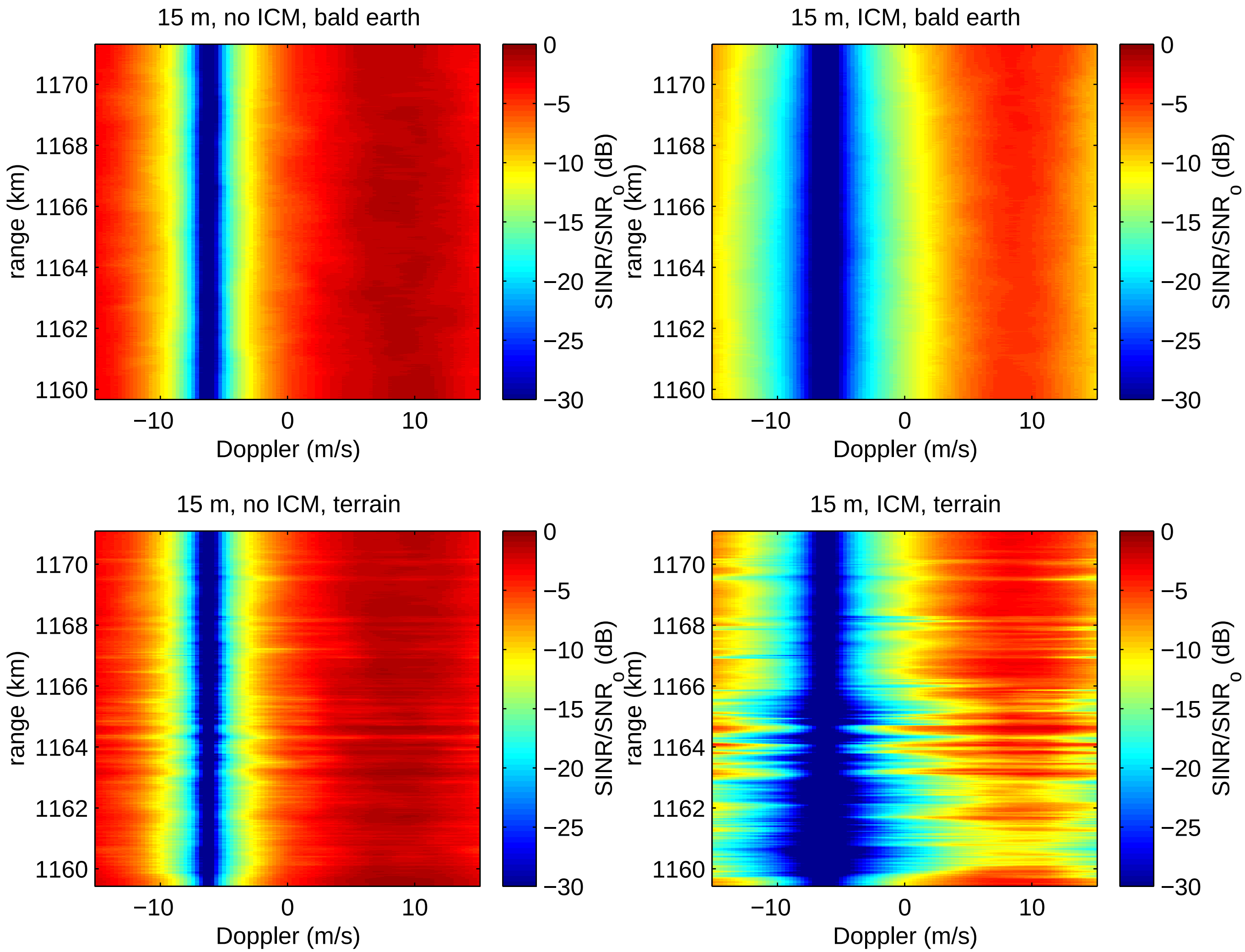
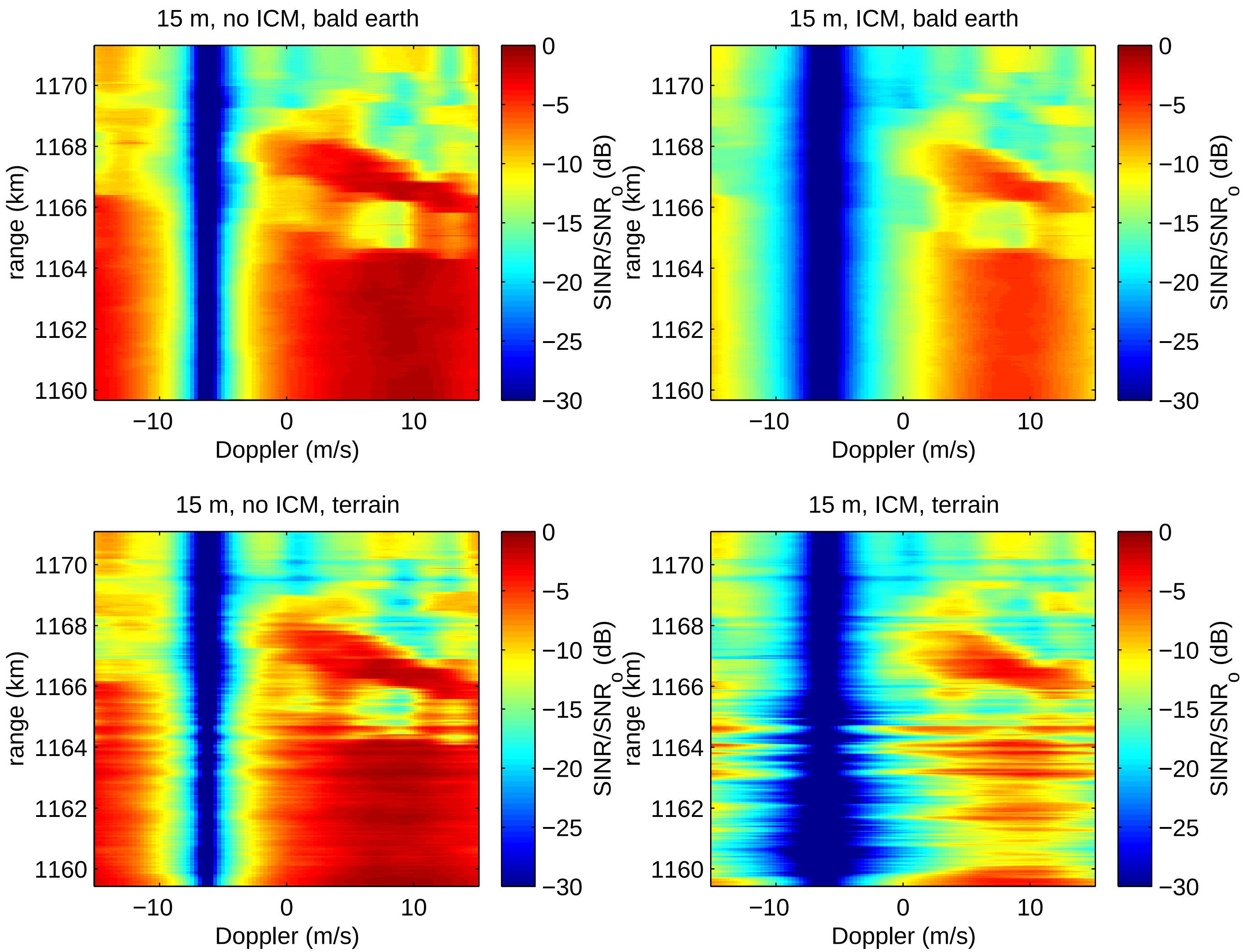


- **~45° grazing angle example - no ground traffic**
- **Space-based radar**
- **DoFs: 10 pulses, 5 beams**
- **100 training bins**
- **10 dB diagonal loading**

Ground Traffic Effects Example (cont.)



- ~45° grazing angle example - ground traffic included
- Space-based radar
- DoFs: 10 pulses, 5 beams
- 100 training bins
- 10 dB diagonal loading

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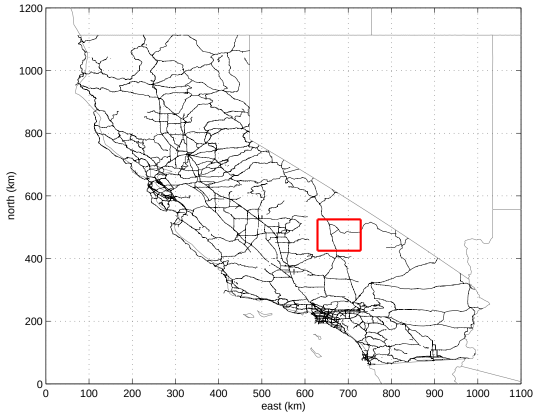
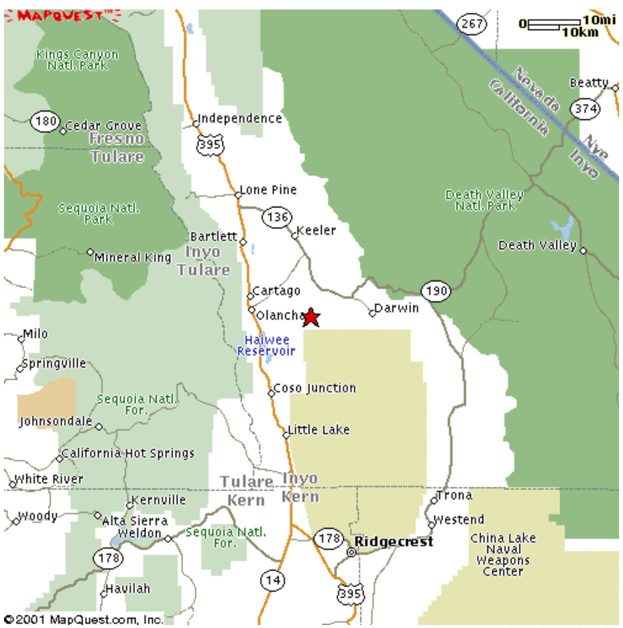
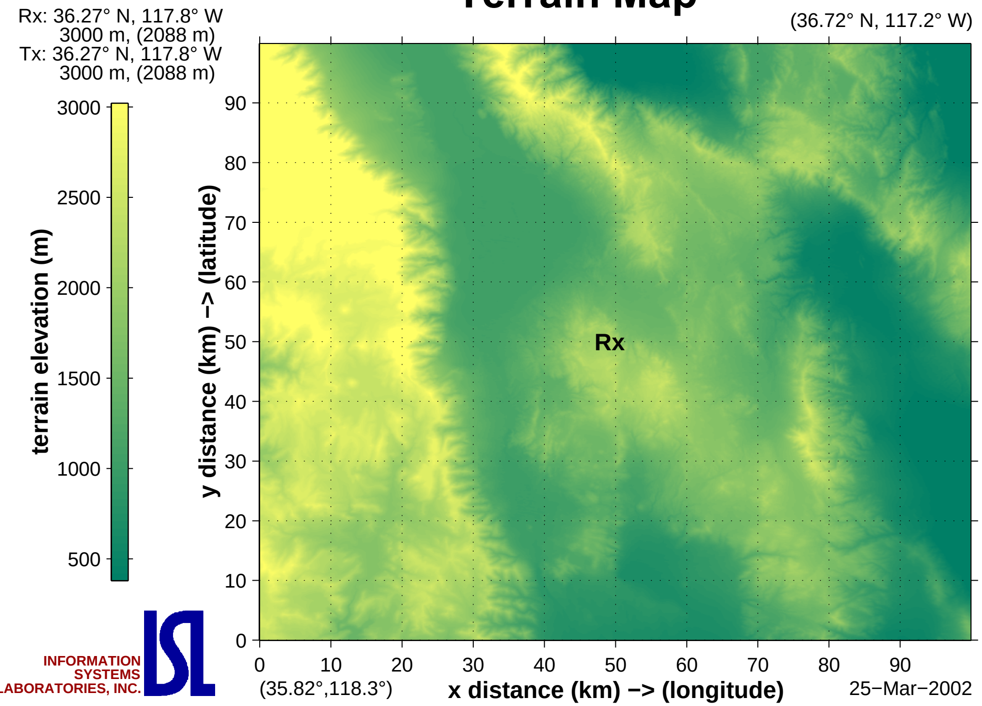
Maps of Simulation Area



Political Maps



Terrain Map



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terrain elevations extracted from NIMA DTED

Range Swath and Steering Direction

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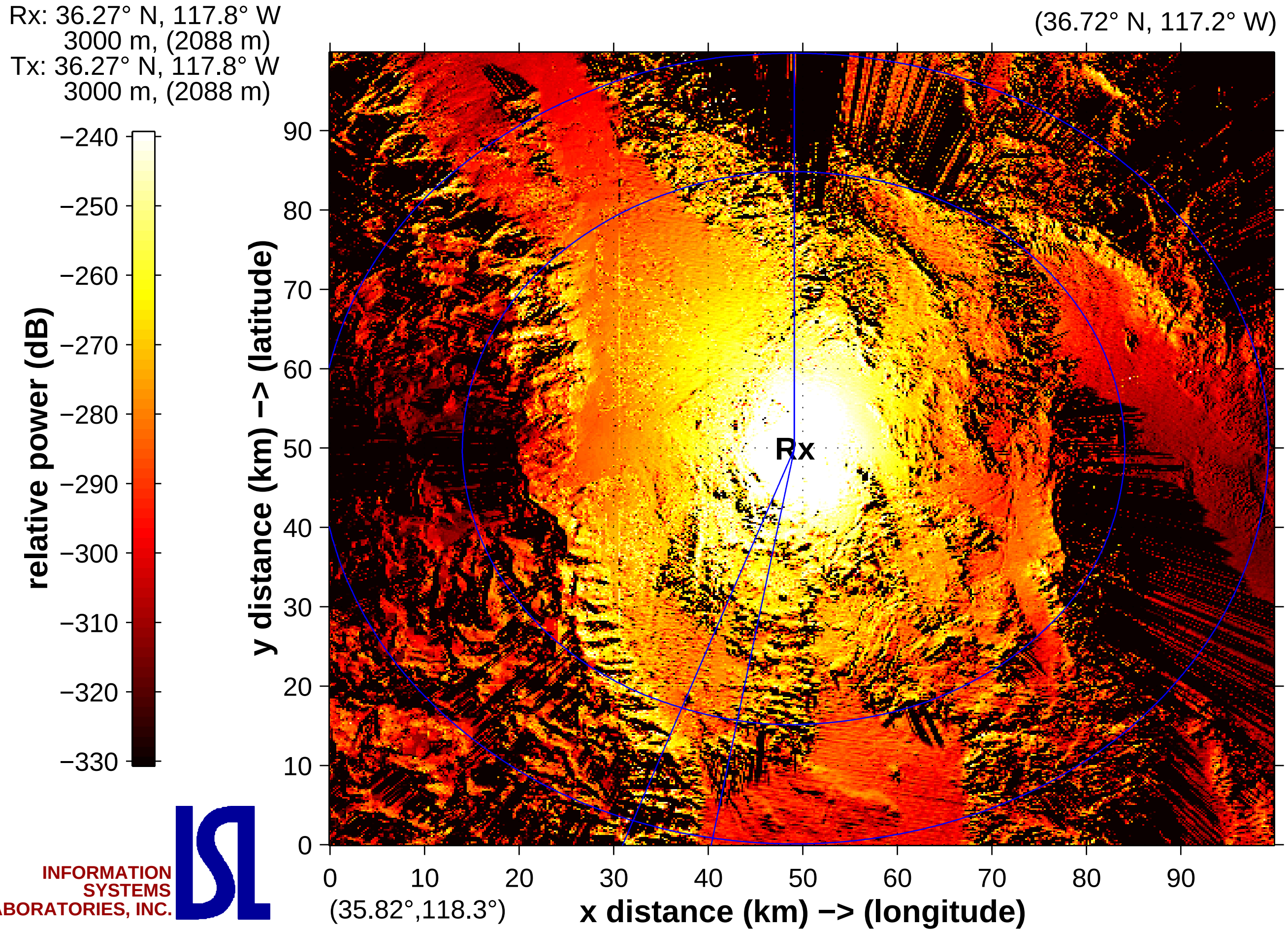

- Scatter map for simulation
- Overlays:
  - range contours for 35 and 50 km shown
- Azimuth contours of main beam shown
- Steering direction is 195°
- Heading is 270°

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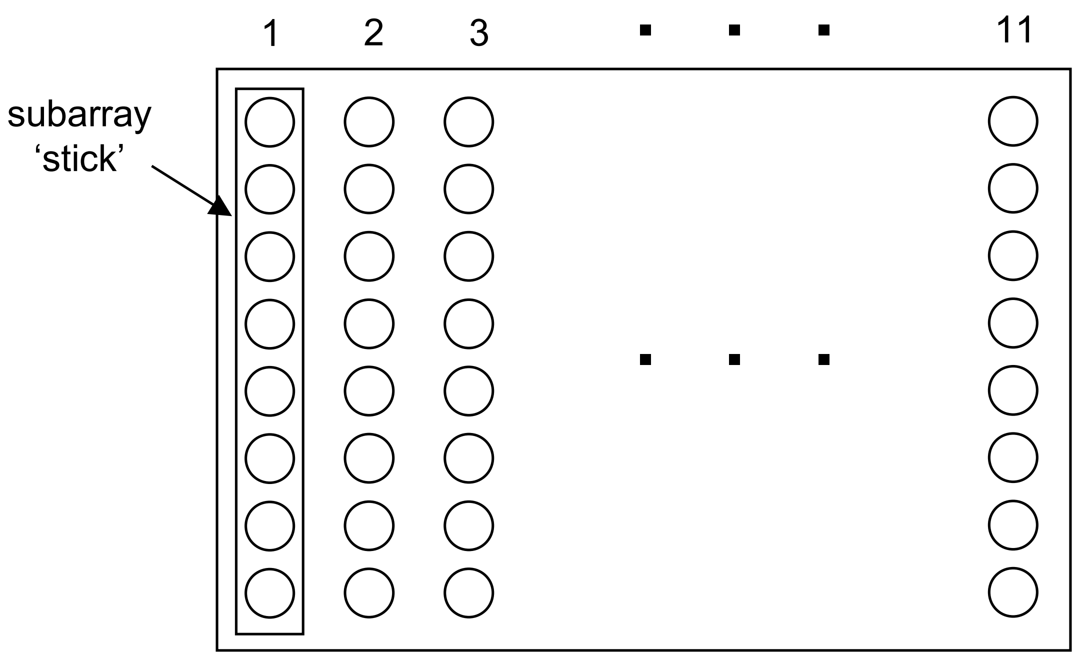
Simulation Parameters

Parmeter	Value
RF frequency	1240 MHz
Bandwidth	10 MHz
PRF	1984 Hz
Peak Power	15 kW
Duty factor	10%
Noise figure	5 dB
System losses	9 dB
Platform speed	100 m/s
Platform altitude	3 km
Transmit aperture	8 vertical x 11 horizontal
Receive aperture*	8 vertical x 1 horizontal
Horizontal antenna spacing	10.9 cm
Vertical antenna spacing	14.07 cm
Number of receive sub-apertures	11
Front-to-back ratio	25 dB

*each channel – 11 channels total

Simulation Antenna Array



- 11 x 8 element array (similar to MCARM)
- Columns of elements combined into single subarray/superelement
- Each column pre-steered to –5° elevation
- Array steered to 195° azimuth on transmite
- Calibration errors introduced to produce overall sidelobe level of approximately 35 dB in azimuth and elevation

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Summary

High fidelity radar simulations

- real-world effects: heterogeneous terrain, ground traffic, targets, ICM, sensor calibration errors
- heterogeneous clutter data set with ground traffic

Future data sets

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- bandwidth effects – decorrelation across array face
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- EM model-based subarray and channel calibration errors
- channel transfer function mismatch
- improved propagation models for SBR
- space-based radar